CONSTRAINING ELECTROWEAK PHYSICS*

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I summarize the status of the Standard Model after the 2003 summer conferences.

The most fundamental observable related to the weak interaction is the muon lifetime, τ_μ. With the electromagnetic two-loop contribution known[1], τ_μ can be used unambiguously to extract the Fermi constant, $G_F = 1.16637(1) \times 10^{-5}$ GeV^{-2}, where the uncertainty is completely dominated by experiment. Adding the fine structure constant, α, one can obtain two relations between the intermediate gauge boson masses, $M_{W,Z}$, and the weak mixing angle[2],

$$\sin^2 \hat{\theta}_W \equiv \hat{s}^2 = \frac{A^2}{M_W^2(1-\Delta\hat{r}_W)}, \qquad \hat{s}^2(1-\hat{s}^2) = \frac{A^2}{M_Z^2(1-\Delta\hat{r}_Z)}. \tag{1}$$

Here $\Delta\hat{r}_W$ and $\Delta\hat{r}_Z$ are electroweak radiative correction parameters (the caret indicates the $\overline{\text{MS}}$ scheme) and the dimensionful quantity $A^2 = \frac{\pi\alpha}{\sqrt{2}G_F} = (37.2805 \pm 0.0003 \text{ GeV})^2$ is known precisely. Most of the Z-pole asymmetries are basically measurements of $\sin^2\theta_e^{\rm eff} = \hat{\kappa}_e \hat{s}^2$, where $\hat{\kappa}_f$ denotes a flavor dependent form factor. Since furthermore M_Z is known to great accuracy, the second Eq. (1) implies that the Z-pole asymmetries effectively determine,

$$\Delta\hat{r}_Z = \frac{\alpha}{\pi}\hat{\Delta}_\gamma + F_1(m_t^2, M_H, \ldots). \tag{2}$$

Asymptotically for large top quark masses, m_t, the function, F_1, grows like m_t^2. This effect has been absorbed into G_F, but now reappears in $\Delta\hat{r}_Z$ when M_Z is computed in terms of it. The first Eq. (1) shows that a determination of the W boson mass can then be used to measure

$$\Delta\hat{r}_W = \frac{\alpha}{\pi}\hat{\Delta}_\gamma + F_2(\ln m_t, M_H, \ldots), \tag{3}$$

where indeed F_2 has a milder m_t dependence. F_1 and F_2 are complicated functions of the Higgs boson mass, M_H, which are asymptotically logarithmic. Eqs. (2) and (3) also show that M_H can be extracted from the precision

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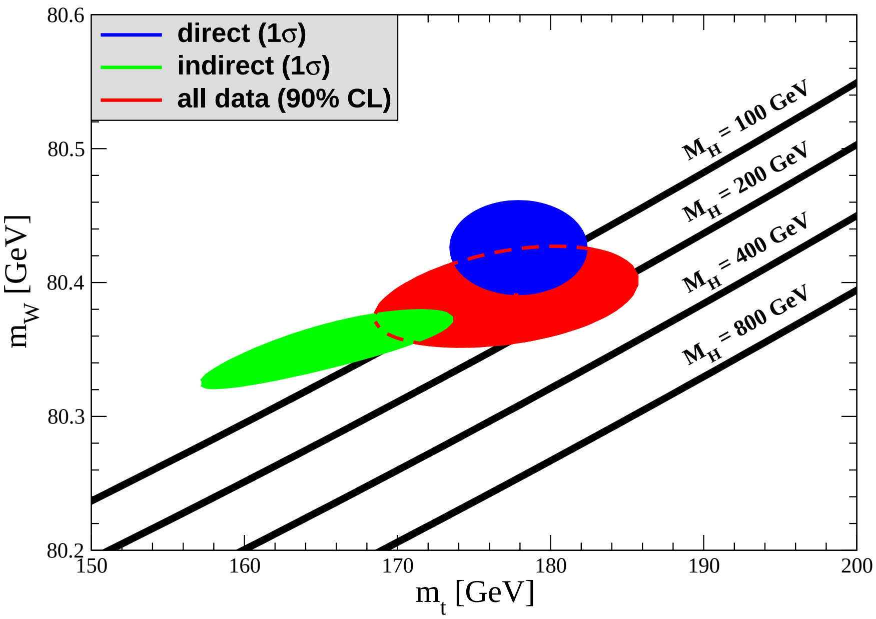

Figure 1. One-standard-deviation (39.35%) region in M_W as a function of m_t for the direct and indirect data, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data. The Standard Model (SM) prediction for various values of M_H is also indicated. The widths of the M_H bands reflect the theoretical uncertainty from $\alpha(M_Z)$. The direct $m_t = 177.9 \pm 4.4$ GeV is the Tevatron average and includes the run I reanalysis of the DØ lepton plus jets channel[3], as well as first results[4] from run II. All correlations and a common 0.6 GeV uncertainty due to the conversion from the pole to the $\overline{\mathrm{MS}}$ mass definition are taken into account.

data only when $\hat{\Delta}_\gamma/\pi = \alpha^{-1} - \hat{\alpha}(M_Z)^{-1}$ is known accurately. Breakdown of the operator product expansion for light quarks, however, introduces an uncertainty in $\hat{\alpha}(M_Z)$ (cf. Fig. 1). It is correlated with the uncertainty in the hadronic two-loop contribution to the muon anomalous magnetic moment, $g_\mu - 2$, which is the limiting factor in the interpretation of the present world average (dominated by the 1999 and 2000 data runs[5] of the E 821 Collaboration at BNL), $(g_\mu - 2)/2 = (1165920.37 \pm 0.78) \times 10^{-9}$. An evaluation of the

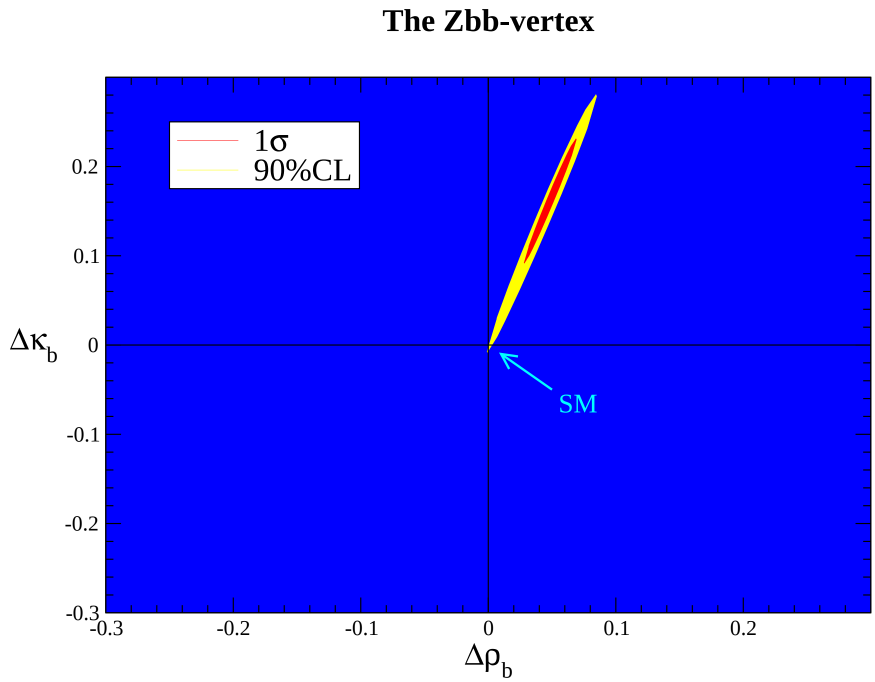

Figure 2. Constraints on new physics contributions to $\kappa_b = 1+\Delta\kappa_b$ (the radiative correction multiplying the weak mixing angle entering the $Zb\bar{b}$ vertex) and $\rho_b = 1 + \Delta\rho_b$ (the overall normalization of the partial $Z \to b\bar{b}$ decay width). $\Delta\kappa_b = \Delta\rho_b = 0$ in the SM by definition.

SM prediction[6] using $e^+e^- \to$ hadrons cross-section information (dominated by the recently reanalyzed CMD 2 data[7]) suggests a 1.9 σ discrepancy with experiment. On the other hand, an alternative analysis[6] based on τ decay data and isospin symmetry (CVC) indicates no conflict (0.7 σ). Thus, there is also a discrepancy (2.8 σ) between the 2π spectral functions obtained from the two methods. It is important to understand the origin of this difference and to obtain additional experimental information. Fortunately, due to the suppression at large s (from where the conflict originates) the difference is only 1.7 σ as far as $g_\mu - 2$ is concerned. Note also that part of this difference is due to older e^+e^- data[6]. Isospin violating corrections have been estimated

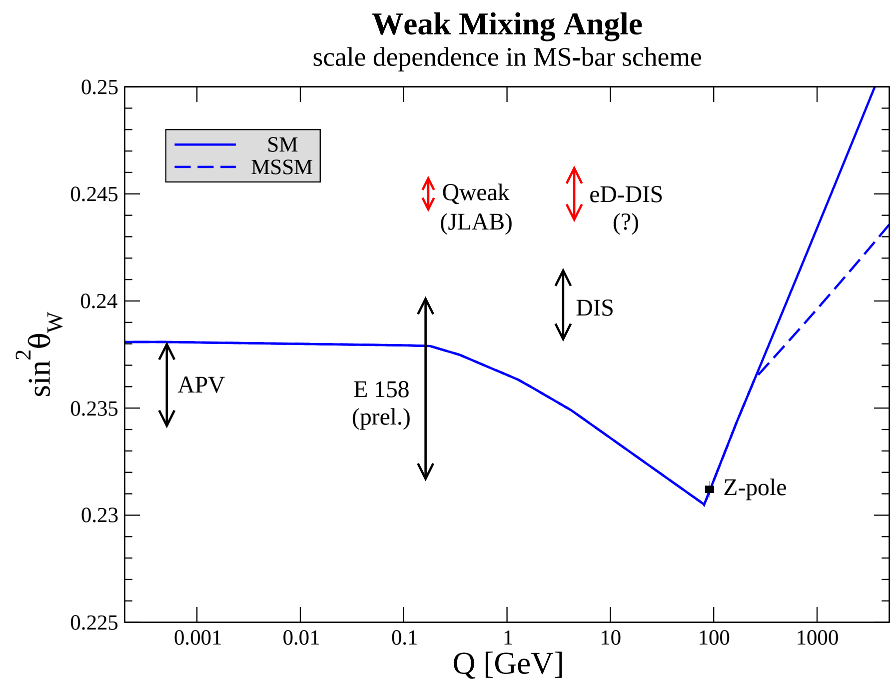

Figure 3. Calculated running of the weak mixing angle in the SM, defined in the $\overline{\text{MS}}$ renormalization scheme (the dashed line indicates the reduced slope typical for the Minimal Supersymmetric Standard Model, MSSM). Shown are the results from atomic parity violation (Cs[16] and Tl[17]), deep inelastic neutrino-nucleon scattering[15] (νN-DIS), the preliminary result of the first run of polarized Møller scattering[18] at SLAC (E 158), and from the Z-pole[11]. Qweak is the future measurement of the weak charge of the proton in low-energy polarized electron-proton scattering at JLAB, while eD-DIS refers to a possible polarized electron-deuteron experiment (the latter two have arbitrarily chosen vertical locations).

and found to be under control[8], where the largest effect is due to higher-order electroweak corrections[9] but introduces a negligible uncertainty[10]. An additional uncertainty is induced by the hadronic three-loop light-by-light type contribution. Averaging the results from the e^+e^- and τ based analyzes yields the SM prediction, $(g_\mu - 2)/2 = (1165918.83 \pm 0.49) \times 10^{-9}$, where the error excludes parametric ones (which are accounted for in the fits). The small

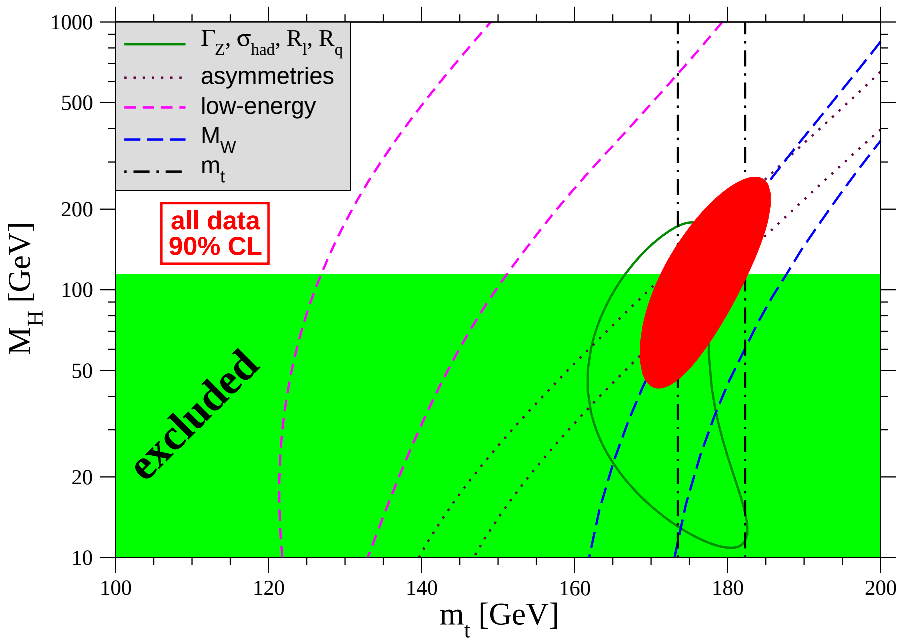

Figure 4. One-standard-deviation (39.35%) uncertainties in M_H as a function of m_t for various inputs, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data. $\alpha_s(M_Z) = 0.120$ is assumed except for the fits including the Z-lineshape data. The 95% direct lower limit[14] from LEP 2 is also shown.

overall 1.6 σ discrepancy between theory and experiment could be due to fluctuations or underestimates of the theoretical uncertainties. On the other hand, $g_\mu - 2$ is affected by many types of new physics and the deviation might also arise from physics beyond the SM.

Another longstanding deviation is observed[11] in Z decays to $b\bar{b}$ pairs. The forward-backward cross-section asymmetry at LEP 1, $A_{FB}^{(b)}$, is 2.2 σ below the SM expectation, while the combined left-right forward-backward asymmetry, A_b, at the SLC and the $Z \to b\bar{b}$ partial width, R_b, are in reasonable agreement. Thus, it is difficult to explain this deviation by new physics effects. As can be seen from Fig. 2, the model independent form factor determinations are

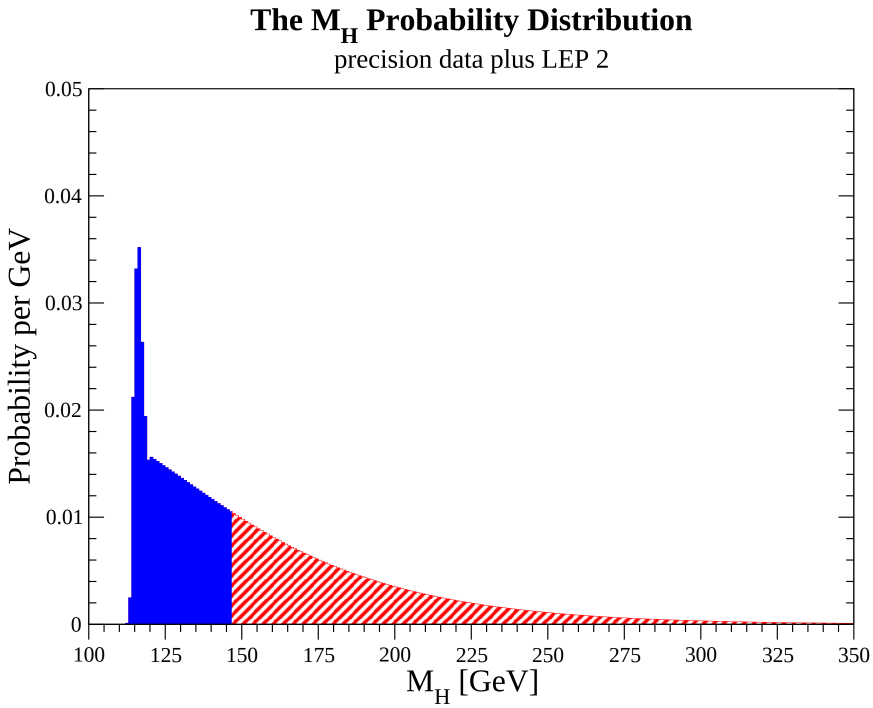

Figure 5. Probability density[19] for M_H obtained by combining precision data with the finalized direct search results[14] at LEP. The peak is due to the candidate Higgs events seen at LEP 2. The two differently colored and patterned areas contain 50% probability each.

marginally consistent with the SM, while large effects (generally too large to arise from radiative corrections) are needed to explain the central values. Note, however, that the average of $A_{FB}^{(b)}$ measurements at LEP 2 is also low ($1.6\ \sigma$) and R_b is $2.1\ \sigma$ high.

The total hadronic cross-section, $\sigma_{\rm had}$, at LEP 2 shows another $1.7\ \sigma$ excess, which is only marginally significant, but in contrast to most other measurements at LEP 2 it is an $\mathcal{O}(1\%)$ measurement and therefore precise enough to be sensitive to TeV scale physics. Interestingly, $\sigma^0_{\rm had}$ on top of the Z pole is also $1.9\ \sigma$ high. The left-right cross-section asymmetry from the SLD Collaboration for hadronic[12] and leptonic[13] final states show a combined

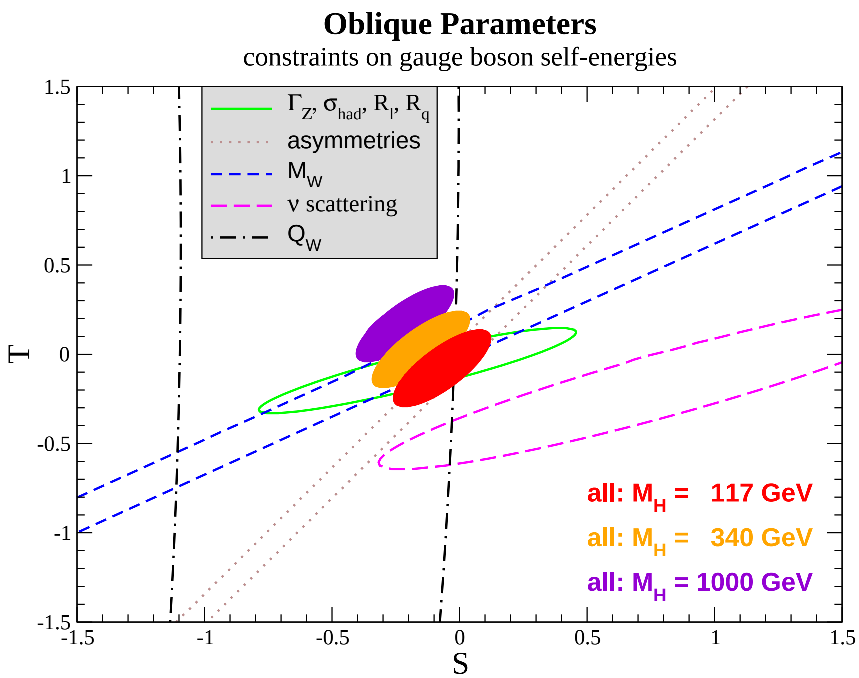

Figure 6. 1 σ constraints (39.35%) on S and T from various inputs. The contours assume $M_H = 117$ GeV except for the central and upper 90% CL contours allowed by all data, which are for $M_H = 340$ GeV and 1000 GeV, respectively. In all cases $U = 0$ is assumed and α_s is constrained using the τ lifetime as additional input.

deviation of 1.9 σ from the SM prediction. In contrast to $A_{FB}(b)$ it favors small values of M_H, which are excluded by the direct searches[14] at LEP 2, $M_H \geq 114.4$ GeV (95% CL). The largest deviation[15] (2.9 σ) is currently in the left-handed effective four-Fermi ν-quark coupling, $g_L^2 = 1/2 - \hat{s}^2 + 5\hat{s}^4/9$, while g_R^2 agrees with the SM prediction. Presently, g_L^2 is the most precise measurement of $\hat{s}^2$ off the Z-pole (see Fig. 3).

The various deviations described above notwithstanding, it must be stressed that the overall agreement between the data and the SM is excellent. The χ^2 per degree of freedom of the global best fit to all data is 45.5/45, where the probability for a larger χ^2 is 45%. The data favors the range,

$M_H = 113^{+56}_{-40}$ GeV, where the central value is very close to the lower LEP 2 exclusion limit[14] (see Fig. 4). If one includes the Higgs search information[14] from LEP, one obtains the probability density in Fig. 5.

Allowing new physics effects in the gauge boson self-energies gives rise (in leading order in the new physics) to three parameters[20], S, T, and U, which are defined to vanish in the SM. Assuming $M_H = 117$ GeV,

$$S = -0.13(10) \;\; [-0.08], \qquad T = -0.17(12) \;\; [+0.09], \qquad U = 0.22(13) \;\; [+0.01],$$

where in brackets the shifts are shown for $M_H = 300$ GeV. All deviate by more than 1 σ from zero but this is a correlated effect (see Fig. 6 for $U = 0$).

Acknowledgments

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